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Anthony J. Colozza
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

J. Appelbaum and M. Crutchik
Tel Aviv University
Tel Aviv, Israel

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A PHOTOVOLTAIC CATENARY-TENT ARRAY FOR THE MARTIAN SURFACE

Anthony J. Colozza
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

J. Appelbaum and M. Crutchik
Tel Aviv University
Faculty of Engineering
Tel Aviv, Israel

ABSTRACT

To provide electrical power during an exploration mission to Mars a deployable tent-shaped structure with a flexible photovoltaic (PV) blanket is proposed. The array is designed with a self-deploying mechanism utilizing pressurized gas expansion. The structural design for the array uses a combination of cables, beams, and columns to support and deploy the PV blanket. Under the force of gravity a cable carrying a uniform load will take the shape of a catenary curve. A catenary-tent collector is self shading which must be taken into account in the solar radiation calculation. The shape and the area of the shadow on the array has been calculated and used in the determination of the global irradiance on the array. The PV blanket shape and structure dimensions were optimized to achieve a configuration which maximizes the specific power (W/kg). The optimization was performed for three types of PV blankets (silicon, gallium arsenide over germanium, and amorphous silicon) and two types of structural materials (carbon composite and aramid fiber composite). The results show that the catenary shape of the PV blanket corresponding to zero end angle at the base with respect to the horizontal results in the highest specific power. The tent angle is determined by optimizing the specific mass and the output power for maximum specific power. The combination of carbon fiber structural material and amorphous silicon blanket produces the highest specific power.

INTRODUCTION

The ability to establish an outpost on the Martian surface is initially dependent on the availability of an adequate power source. The ideal power supply would require very little implementation time and have a high reliability for operation. Also, to meet the constraints of launching and transportation it would need to be lightweight and capable of being stowed in a relatively small volume. A photovoltaic (PV) array whose configuration is optimized for maximum specific power (W/kg) can meet these requirements.

This analysis was performed to optimize a tent shaped PV array for maximum specific power at the Viking Lander 1 (VL1) location (Latitude 22.3°N, Longitude 47.9°W) on the Martian surface. The array is designed with a self-deploying mechanism utilizing pressurized gas expansion as the deployment mechanism. The array structural design uses a combination of cables, beams, and columns to support and deploy the PV blanket. The array is stowed with the blanket either folded or rolled, depending on the particular blanket's flexibility. Details on this design are given in Ref. 1.

Each structural component of the design was analyzed to determine the size necessary to withstand the various forces it would be subjected to. Through this analysis each component's weight was determined based on the structural loads it would experience both during deployment and once fully deployed. Once this was accomplished, an analysis of the output power of the PV blanket was performed. This included analyzing the global radiation (direct, diffused, and reflected) as well as any partial shading which would occur on the PV blanket due to its catenary shape. The combination of output power and structural weight were used to achieve a configuration which maximizes the specific power of the array at the given location.

The optimization was performed with two types of structural materials (carbon VHS composite and aramid fiber composite) and with three types of PV blankets (silicon, gallium arsenide over germanium, and amorphous silicon) for the VL1 location on the Martian surface.

STRUCTURE ANALYSES

A tent-shaped structure with a flexible PV blanket for solar power generation was proposed in Ref. 1. An artists conception of the array is shown in Fig. 1. The array structure was designed to be capable of supporting the PV blanket and have the ability for autonomous deployment and compact stowage. The PV blanket is held in place on the structure by a series of cables evenly spaced along the blanket length. Under the force of gravity these cables, which are supporting the weight of the PV blanket, will take the shape of a catenary curve which is shown in Fig. 2 and given by $z = f_c(y)$ where:

$$f_c(y) = K\{\cosh[(D/2 - y)/K] - 1\}$$

where K is the catenary constant determined by $f_c(0) = H$. The beams on which the cables are attached are supported by a series of telescoping columns which also act as the deployment mechanism for the array [1].

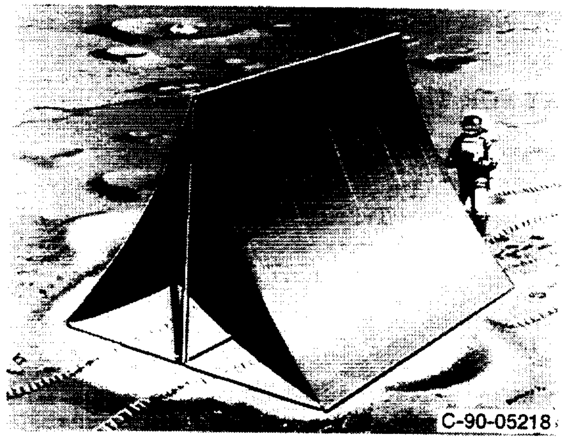

Figure 1.—Artist's conception of the self-deploying PV tent array.

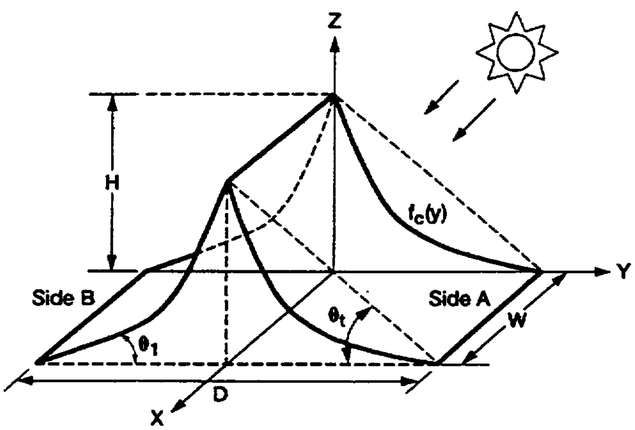

Figure 2.—Tent structure and PV blanket geometry.

The structural analysis takes into account the tension in the blanket and support cables, weight of the structural components and PV blanket, forces incurred during deployment, and wind loading. It should be noted that on Earth, wind loading constitutes the main loading force. On Mars, however the wind loading is not nearly as great due to substantially lower atmospheric density of about 7 to 9 mbar. The structure design parameters shown in Fig. 2 are: the tent base length D, the tent width W, the tent height H, the tent angle θ_t and the blanket end angle θ_1. The details of the structural analysis used to determined the component weights and dimensions is given in Ref. 1. This study shows that the optimal blanket shape, which is characterized by the end angle θ_1, for minimum structure specific mass is obtained for $\theta_1 = 0$, i.e., a blanket having a natural catenary shape. This result is shown in Fig. 3 for carbon VHS composite material, GaAs/Ge PV blanket, $\theta_t = 15°$ and 20 m/s wind speed. Similar trends were found for all other material/PV blanket combinations.

SOLAR POWER ANALYSIS

A catenary-tent collector is self shading (e.g., side B is shaded by side A in Fig. 2). This must be taken into account when determining the PV blanket output power. A detailed analysis of the shape and the area of the shadow on the array and hence the beam irradiance falling on the blanket is given in Ref. 2. The diffuse and albedo irradiance were also calculated to determine the global irradiance on the array. A solar radiation model for Mars was developed [3] and the solar output power of the PV blanket was determined based on this model. It was also found that the collected energy varies very little with the azimuthal orientation of the tent and with the blanket end angle, θ_1. The details of this part of the analysis will be published in a subsequent paper. Figure 4 shows the variation of the yearly average global irradiance as a function of the blanket end angle, θ_1, for location VLl and tent angle $\theta_t = 17°$. Similar results occurred for tent angles other then 17°.

OPTIMAL CATENARY-TENT ARRAY

The shape of the PV blanket is determined by an optimization between the change in both array structure weight and output power over various array geometries. Since the blanket end angle, θ_1, greatly affects the specific mass of the structure (Fig. 3) but has little influence over the array output power (Fig. 4), the optimal shape of the blanket takes the natural catenary curve, $\theta_1 = 0°$, which minimizes specific mass.

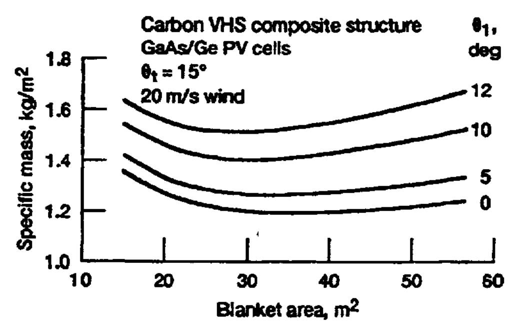

Figure 3.—Array specific mass variation with PV blanket end angle and area.

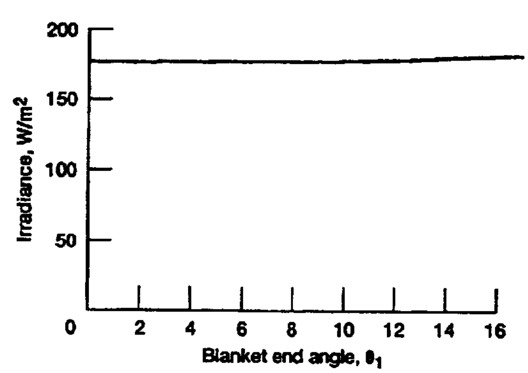

Figure 4.—Variation of the yearly average global irradiance as a function of PV blanket end angle.

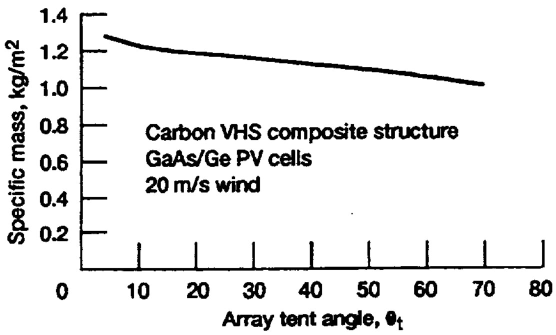

Figure 5.—The effect of the tent angle on the specific mass of the array.

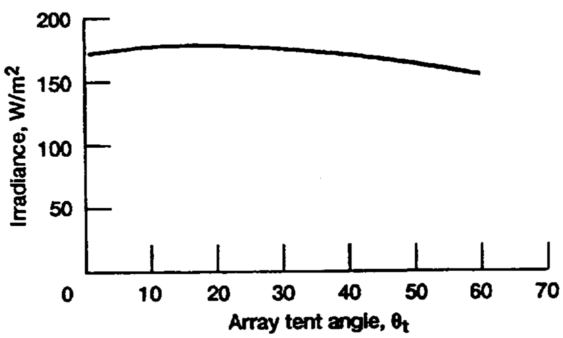

Figure 6.—Variation of the yearly average global irradiance as a function of tent angle.

Structure specific mass (kg/m^2 of blanket) and array specific power (W/m^2) are strong functions of tent angle, θ_t. A typical effect of the tent angle on the specific mass is shown in Fig. 5 for carbon VHS composite, GaAs/Ge PV blanket and wind speed of 20 m/s. The figure shows that the specific mass decreases with increasing of tent angle, and the tendency is toward a bifacial vertical array. This is due to the fact that as the tent angle θ_t approaches 90° more of the loading is transmitted as compression in the vertical columns as opposed to bending which therefore requires less structural mass to support the array. The results for other material and PV blanket combinations were similar.

A stationary collector, either flat or curved (e.g., catenary) possesses an optimal tilt angle with respect to maximum global irradiance depending on the variation of the solar radiation throughout the year at the location latitude. The variation of the yearly average global irradiance as a function of the tent angle, θ_t, is shown in Fig. 6. The optimal array-tent angle, θ_{tm},is determined based on both the specific mass (Fig. 5) and the array output power (Fig. 6) and is expressed as the specific power of the PV array in W/kg. This is shown in Fig. 7 for carbon VHS composite and GaAs/Ge at VLl and for wind speed of 20 m/s. Similar curves can be produced for all other structural material/PV blanket combinations.

With the optimal tent angle for maximum specific power known, the remaining parameters D, W, and H can be determined. Since output power per area of PV blanket is independent of these parameters they are determined by minimizing array structure mass per area of PV blanket. The procedure for this is given in Ref. 1.

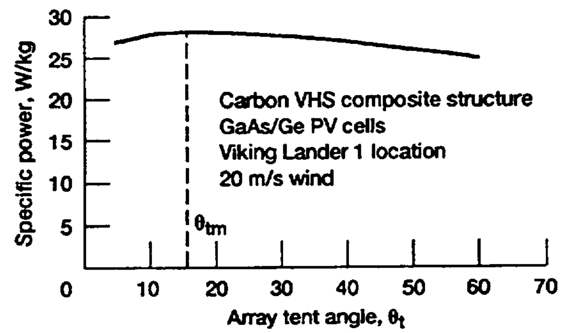

Figure 7.—Variation in specific power as a function of tent angle.

In our study we analyzed three types of PV blankets made of Si, GaAs/Ge, and a-Si, and two types of structure materials made of carbon VHS composite and aramid fiber composite. The location on Mars is at VLl and the variation in solar radiation corresponds to a full Martian year. The specifications of the structural materials and the PV blankets are given in Tables I(a) and (b). The results of the optimization process for the PV tent array and all structural material/PV blanket combinations is summarized in Table II.

DISCUSSION

Through the analysis it was determined that of all the structural material/PV blanket combinations analyzed the highest specific power for the PV array is obtained using carbon VHS composite structural material and an amorphous silicon PV blanket. The second best solution for the PV array is the combination of carbon VHS composite structure and GaAs/Ge solar cells. The results for the amorphous silicon PV blanket requires an explanation. The optimal solution for this combination is obtained for $\theta_t \sim 90°$. The reason for it resides in the fact that amorphous silicon has a much lower blanket specific mass than the other types of PV blankets. As a result, the specific mass of the structure material decreases much more rapidly with increasing tent angle θ_t than it does with the other PV blankets. The optimal design of the array for maximum specific power with an amorphous silicon PV blanket is therefore obtained for very large tent angles. The values in Table II for amorphous silicon are calculated for $\theta_t = 17°$ this was done to keep the analysis consistent for all types of PV blankets. Even at that low tent angle, the specific power is higher than for the other PV blankets.

In a situation where the array design must be altered or where one or more of the geometry variables are constrained, for example the catenary blanket being annexed to an existing structure, a new optimization would have to be performed based on the remaining unrestricted variables.

TABLE I.—PV BLANKET AND STRUCTURAL MATERIALS

SPECIFICATIONS

(a) Structural materials properties

	Carbon VHS composite	Aramid fiber composite
Modulus, GPa	124	76
Yields strength, GPa	1.90	1.38
Density, kg/m^3	1530	1380

(b) PV blanket specifications

	Silicon	Gallium arsenide over germanium	Amorphous silicon
Efficiency, percent	14.5	19.5	10.0
Blanket specific mass, kg/m^2	0.427	0.640	0.040
Cell thickness, μm	250	~250	2

TABLE II.—OPTIMAL ANALYSIS RESULTS FOR THE VARIOUS PV BLANKET STRUCTURAL

MATERIAL COMBINATIONS

	Array width-W, m	Array height-H, m	Array base-D, m	Tent angle-θ_t, deg	Blanket area, m^2	Total specific mass, kg/m^2	Global insolation, w/m^2	Specific power, W/kg
Carbon VHS silicon	3.75	1.39	8.56	18	34.30	0.9704	2054.7	25.6
Carbon VHS GaAs/Ge	3.75	1.16	8.69	15	34.16	1.1995	2069.1	28.1
Carbon VHS amorphous Si	3.75	1.16	8.69	15	34.16	.5726	2069.1	[a]32.8
Aramid fiber silicon	3.50	1.30	7.56	14	31.84	1.1023	2073.3	24.8
Aramid fiber GaAs/Ge	3.50	1.16	8.69	15	31.88	1.2310	2069.1	27.3
Aramid fiber amorphous Si	3.50	1.16	8.69	15	31.88	.6058	2069.8	[a]31.0

[a]Not optimal solution, see text.

The wind speed and the PV blanket cell efficiency have no effect on the optimal values of the array [1]. By increasing the wind velocity, the required structural mass increases and thereby increases the array specific mass. This increase occurs uniformly for all structural materials and PV blanket types. The best combination of structure material and PV blanket remains the same. The PV blanket cell efficiency affects the numerical value of array specific power but not the optimal design point.

CONCLUSIONS

To provide electrical power during an exploration mission to Mars, a deployable tent-shaped structure having a flexible catenary photovoltaic blanket is proposed. The structural design for the array uses a combination of cables, beams, and columns to support and deploy the PV blanket. The PV blanket shape and the array dimensions were optimized to achieve a configuration which maximizes the specific output power (W/kg). The self shading which occurs when using a catenary-tent array was taken into consideration in the direct beam solar radiation calculation. The diffused and reflected (albedo) radiation were also taken into account. The natural catenary shape of the PV blanket, i.e., $\theta_1 = 0°$ is mainly determined by the array specific mass and much less by the output power of the PV blanket. The tent angle θ_t is determined by the combined effect of the specific mass and the output power. Two structural materials (carbon VHS composite and aramid fiber) and three types of PV blankets (Si, GaAs/Ge, and a-Si) were considered in the array analysis for the Martian surface. The combination of carbon VHS composite structural material and amorphous silicon solar cells produces the highest specific power. The Mars environmental data used in the study refers to one location on Mars, VLl, and the yearly average global irradiance.

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2. M. Crutchik and J. Appelbaum "Solar Radiation on a Catenary Collector," NASA TM-10575, 1992.

3. J. Appelbaum, G.A. Landis, and I. Sherman "Solar Radiation on Mars—Update 1991," Solar Energy, Vol. 50, No. 1, 1993, pp. 35–51.

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Anthony J. Colozza, J. Appelbaum, and M. Crutchik

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Sverdrup Technology, Inc.
Lewis Research Center Group
2001 Aerospace Parkway
Brook Park, Ohio 44142

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